Microscopic Reaction Dynamics at SPS and RHIC

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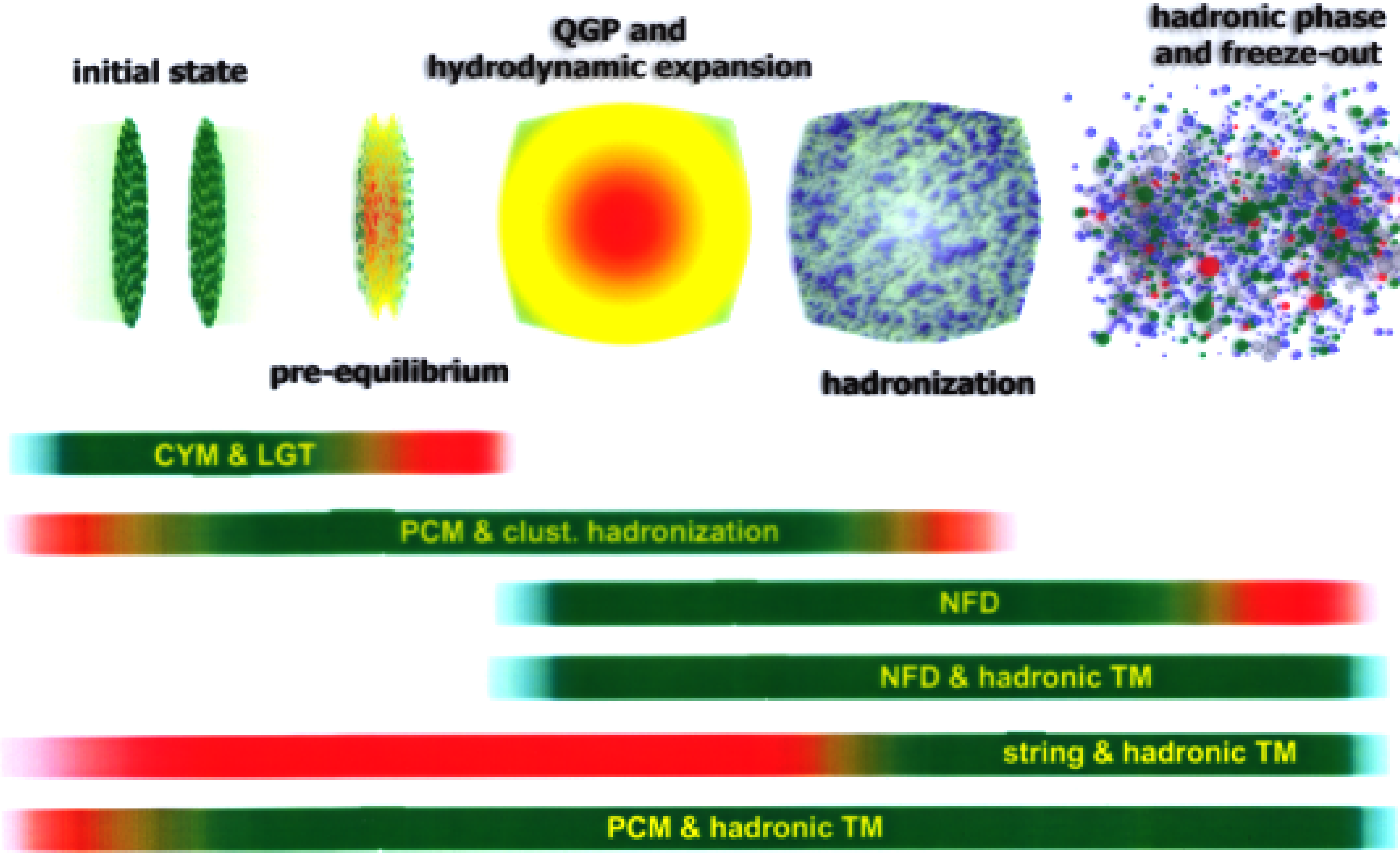
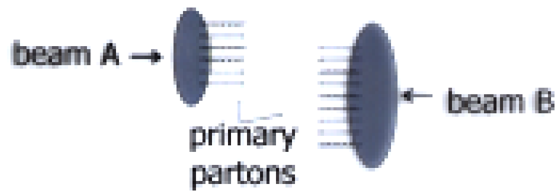
- Overview: Transport Theory at RHIC
- Microscopic Transport Models
- Reaction Dynamics in different approaches:
  - Kinetic Evolution
  - Hadrochemistry and Flavor Dynamics
  - Freeze-out
- Summary

Transport Theory at RHIC

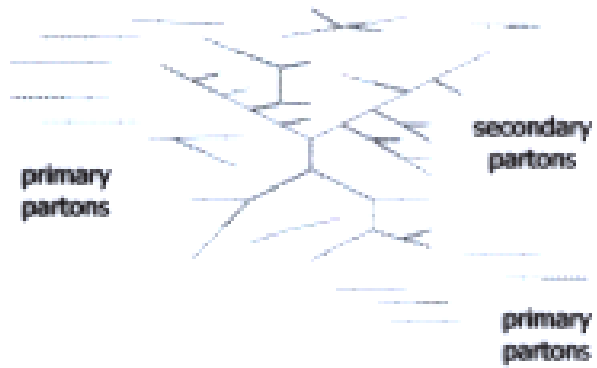


The Parton Cascade Model

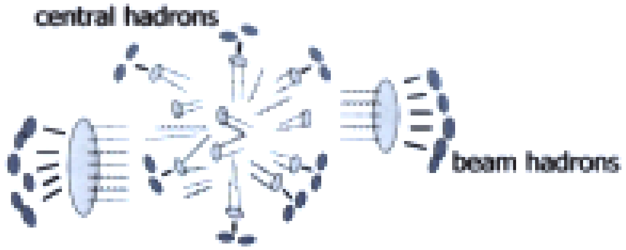
- **initial state**
  - ➢ nucleon structure functions
  - ➢ elastic form factors



- **partonic interactions**
  - ➢ lo pQCD cross sections



- **hadronization**
  - ➢ phase space coalescence with color neutrality constraint



The UrQMD Model

- elementary degrees of freedom: hadrons, const. (di)quarks
- classical trajectories in phase-space (relativistic kinematics)
- initial high energy phase of the reaction is modeled via the excitation and fragmentation of strings
- 55 baryon- and 32 meson species, among those 25 N*, Δ* resonances and 29 hyperon/hyperon resonance species
- full baryon-antibaryon and isospin symmetry
- ➢ ideal for the description of excited hadronic matter

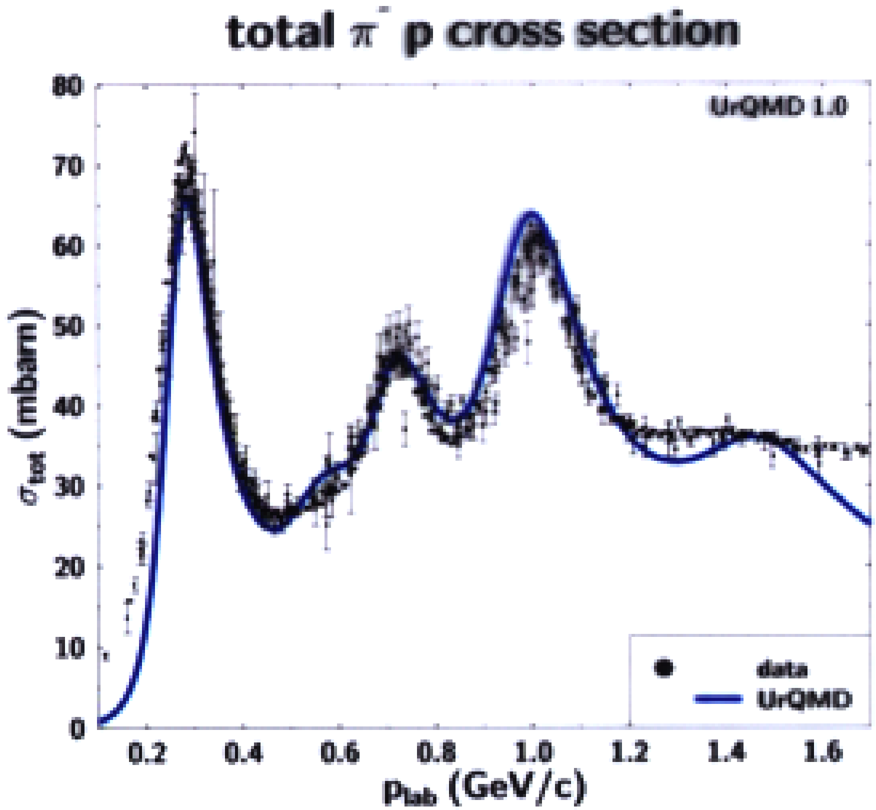
- main physics input and parameters:
  - **cross sections**: total and partial cross sections, angular distributions
  - **resonance parameters**: total and partial decay widths
  - **string fragmentation scheme**: fragmentation functions, formation time

- An interaction takes place if at the time of closes approach d_{min} of two hadrons the following condition is fulfilled:

$$d_{min} = \sqrt{\frac{\sigma_{tot}}{\pi}} \quad \text{with} \quad \sigma_{tot} = \sigma_{tot}(\sqrt{s}, |h_1\rangle, |h_2\rangle)$$

Meson Baryon Cross Section in UrQMD

- model degrees of freedom determine the interaction to be used



Δ*	**width**	**N***	**width**
Δ_{1232}	120 MeV	N^*_{1440}	200 MeV
Δ_{1600}	350 MeV	N^*_{1520}	125 MeV
Δ_{1620}	120 MeV	N^*_{1535}	150 MeV
Δ_{1700}	300 MeV	N^*_{1650}	150 MeV
Δ_{1900}	200 MeV	N^*_{1675}	150 MeV
Δ_{1905}	350 MeV	N^*_{1680}	130 MeV
Δ_{1910}	250 MeV	N^*_{1700}	100 MeV
Δ_{1920}	200 MeV	N^*_{1710}	110 MeV
Δ_{1930}	350 MeV	N^*_{1720}	200 MeV
Δ_{1950}	300 MeV	N^*_{1990}	300 MeV

- calculate cross section according to: $\sigma_{tot}^{MB} = \sum_{R=\Delta,N^*} \frac{2I_R+1}{(2I_B+1)(2I_M+1)} \frac{\pi}{p_{cms}^2} \frac{\Gamma_{R\to MB}\Gamma_{tot}}{(M_R-\sqrt{s})^2+\frac{\Gamma_{tot}^2}{4}}$

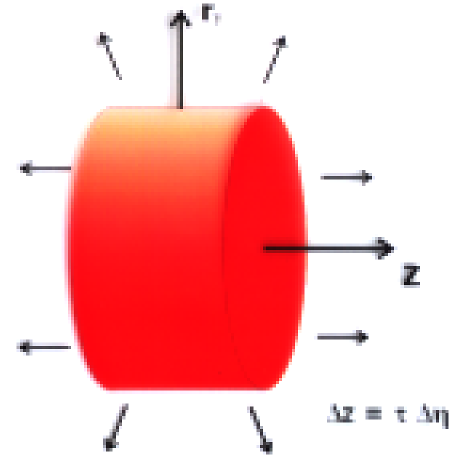
Nuclear Fluid Dynamics

- transport of macroscopic degrees of freedom
- based on conservation laws: $\partial_\mu T^{\mu\nu}=0$ $\partial_\mu j^\mu=0$

- for ideal fluid: $T^{\mu\nu}= (\varepsilon+p)\, u^\mu u^\nu - p\, g^{\mu\nu}$ and $j_i^\mu = \rho_i u^\mu$
- **Equation of State** needed to close system of PDE's: $p=p(T,\rho_i)$

- assume local thermal equilibrium
- initial conditions (i.e. thermalized QGP) required for calculation

- simple case: scaling hydrodynamics
  - assume longitudinal boost-invariance
  - cylindrically symmetric transverse expansion
  - no pressure between rapidity *slices*
  - conserved charge in each *slice*



A combined Macro/Micro Transport Model

Hydrodynamics + **micro. transport (UrQMD)**

Hydrodynamics

- ideally suited for dense systems
  - model early QGP reaction stage
- well defined Equation of State
  - Incorporate 1st order p.t.
- parameters:
  - initial conditions (fit to experiment)
  - Equation of State

micro. transport (UrQMD)

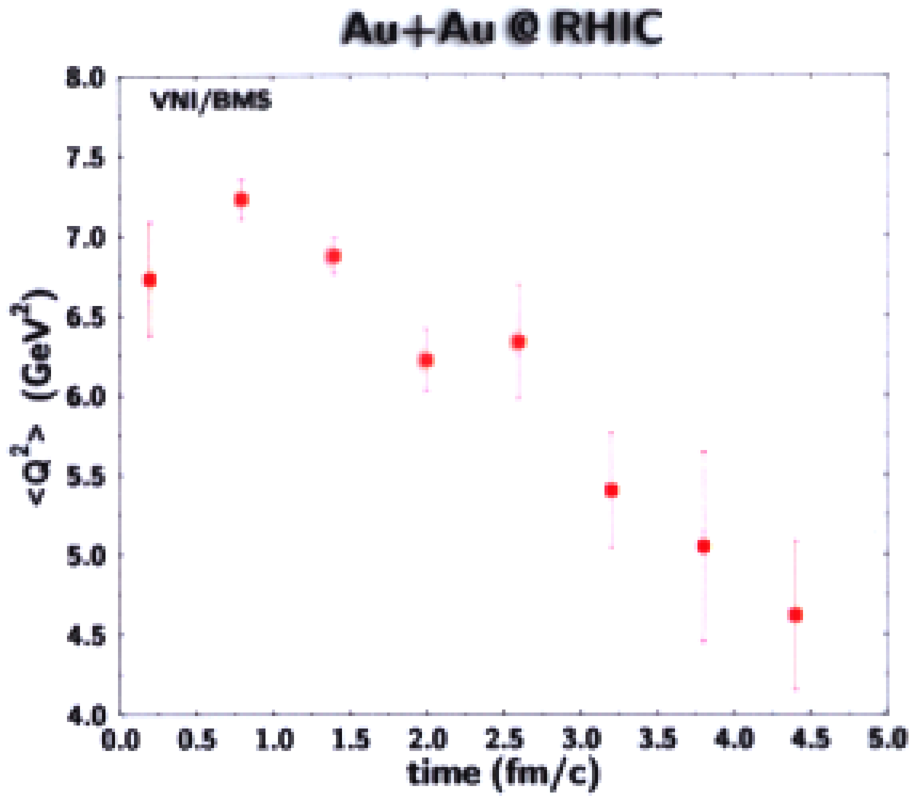
- no equilibrium assumptions
  - model break-up stage
  - calculate freeze-out
- parameters:
  - (total/partial) cross sections
  - resonance parameters (full/partial widths)

matching conditions:

- use same set of hadronic states for EoS as in UrQMD
- perform transition at hadronization hypersurface: generate space-time distribution of hadrons for each cell according to local T and μ_B

➢ use as initial configuration for UrQMD

Reaction Dynamics in a Parton Cascade



process	p+p	Au+Au
$gg \to gg$	41.4%	43.0%
$gg \to g^*$	24.0%	27.0%
$qg \to qg$	29.8%	26.7%
$qq \to qq$	3.2%	2.0%
qqbar→qqbar	0.3%	0.2%

➢ dynamics are gluon dominated

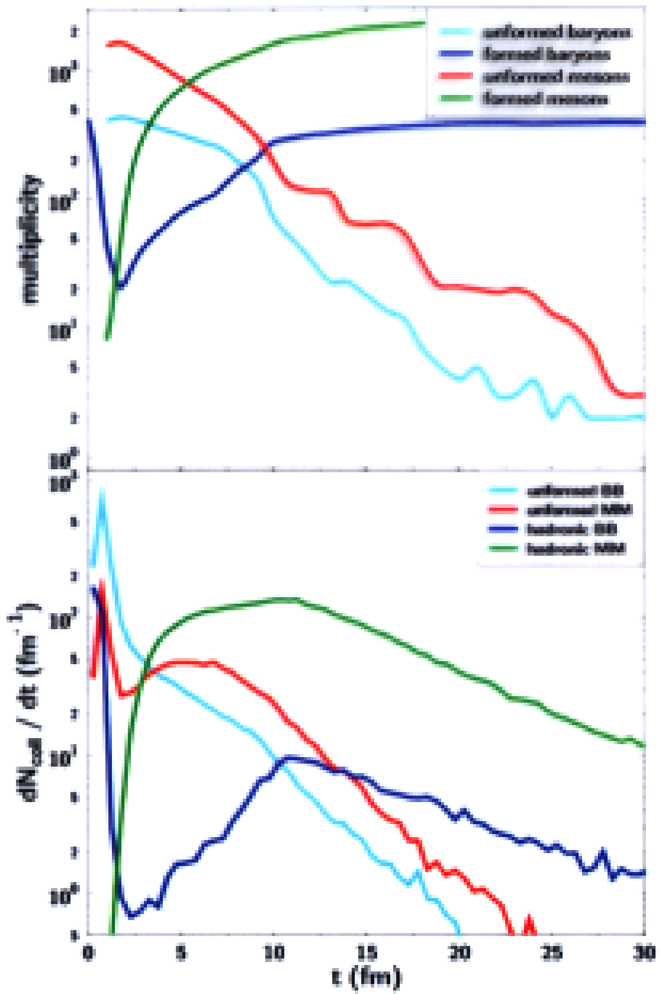
- strong decrease in $<Q^2>$ vs. time:
  - non-equilibrium nature of initial state: early collisions at large Q^2
  - decrease hints at parton rescattering and onset of thermalization
  - Q^2 scale changes strongly during reaction: no unambiguous pQCD scale

Reaction Dynamics in a String/Hadron Model

- early reaction stage dominated by hadrons from string fragmentations (unformed hadrons)
- exponential decrease in unformed hadron multiplicity (formation time)
- hadrons from sea quarks do not interact during formation time
- valence (di)quark rescattering with cross sections according to AQM
  - ➢ only important during initial 2-3 fm/c

- system is meson dominated: multiplicity and collision rate one order of magnitude higher than for baryons

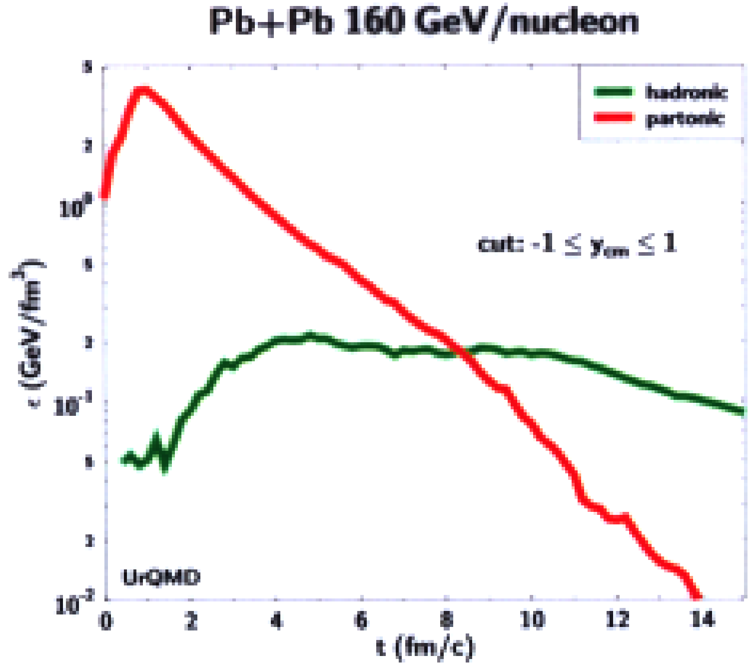
Pb+Pb 160 GeV/nucleon

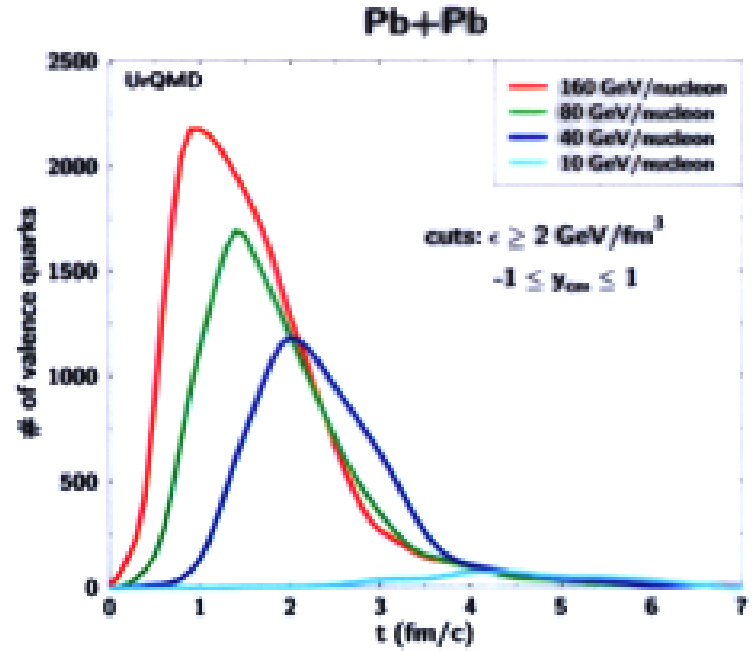


Energy Density in String/Hadron Models

sub-hadronic degrees of freedom:

➢hadrons created in string fragmentations within their formation time

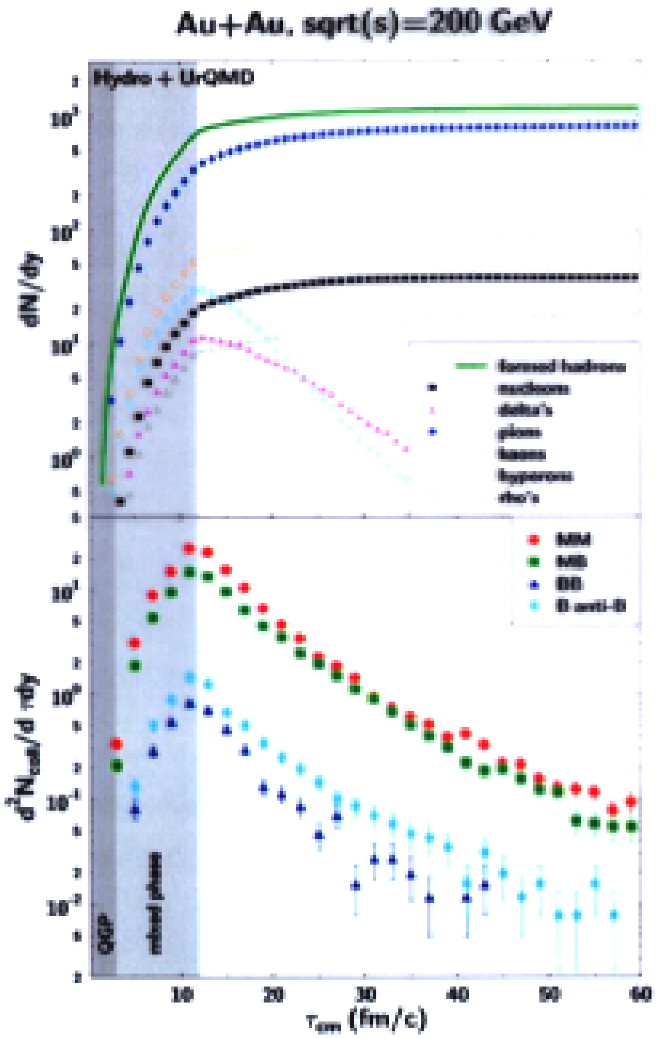




- high energy density dominated by sub-hadronic degrees of freedom
- up to 2000 valence quarks in medium with $\varepsilon > 2$ GeV/fm^3
- Lattice: ε_{crit} caluclated for infinite time / periodic boundaries
- RHIC: dynamic system with short lifetime and finite size

Reaction Dynamics in a Macro/Micro Model

- initial conditions:
  - Quark Gluon Plasma
  - EoS with 1st order phase transition
  - T_C=160 MeV
- hadron multiplicities continue to rise after end of mixed phase
- high population of resonances, primordial and due to hadronic rescattering
- collision rates:
  - peak at end of mixed phase
  - MM and MB interactions dominate
- late kinetic freeze-out after ≈ 35 fm/c

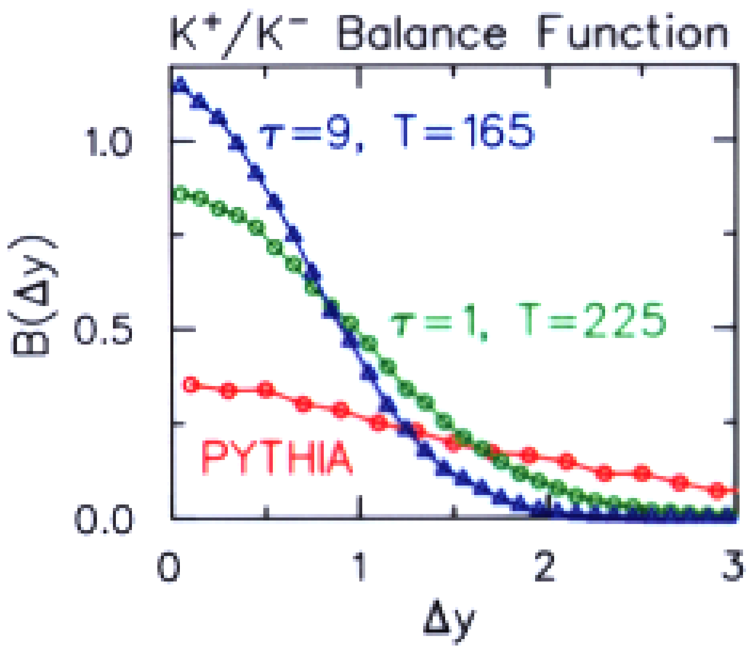


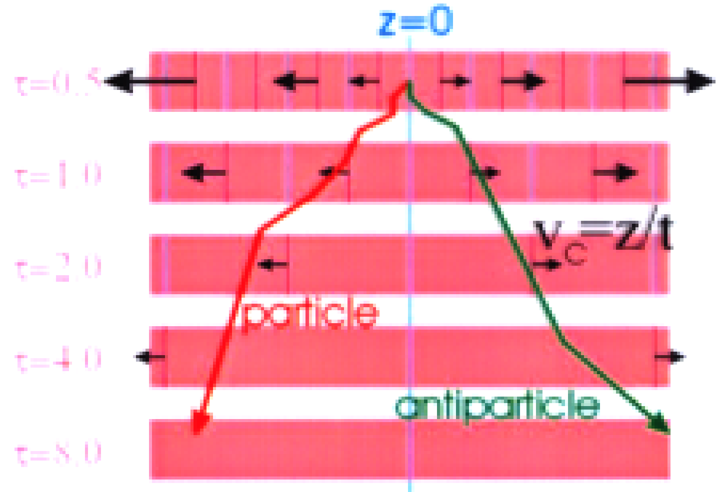
Probing Hadronization Time: Balance Functions

$$B(\Delta y) \equiv \frac{1}{2}\left\{\rho(+Q, y+\Delta y \,|\, -Q, y) - \rho(-Q, y+\Delta y \,|\, -Q, y)\right\}$$

- B(Δy) narrower for late stage hadronization for two reasons:

1. lower temperature: $\langle \Delta y \rangle \approx \sqrt{2T/M}$
2. High initial *dv/dz*: diffusion separates early produced pairs

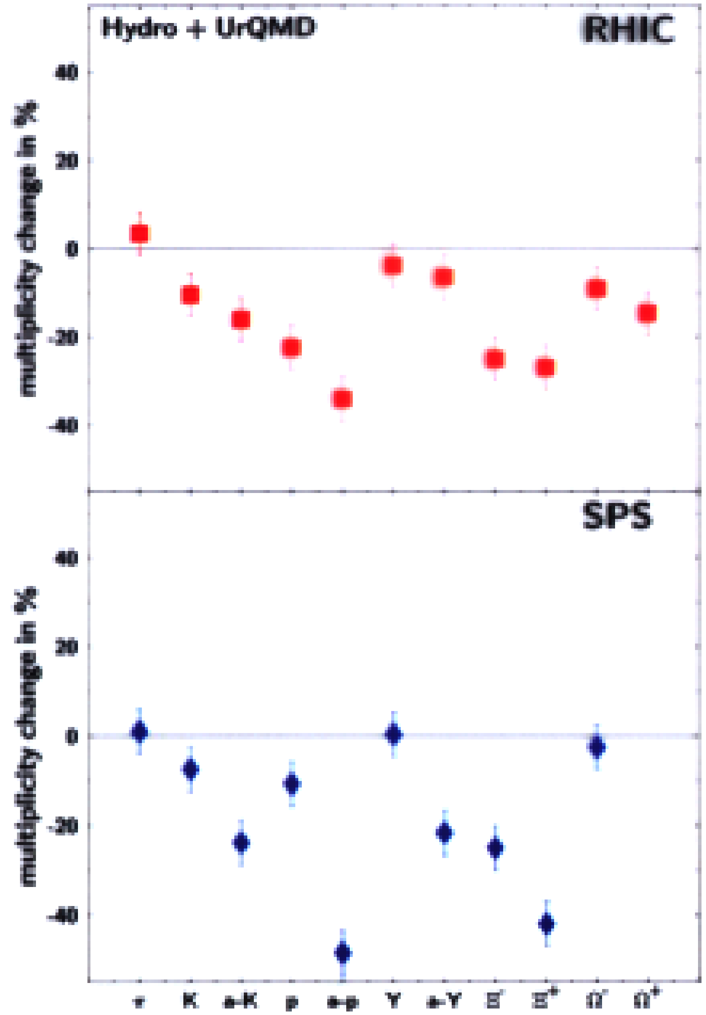




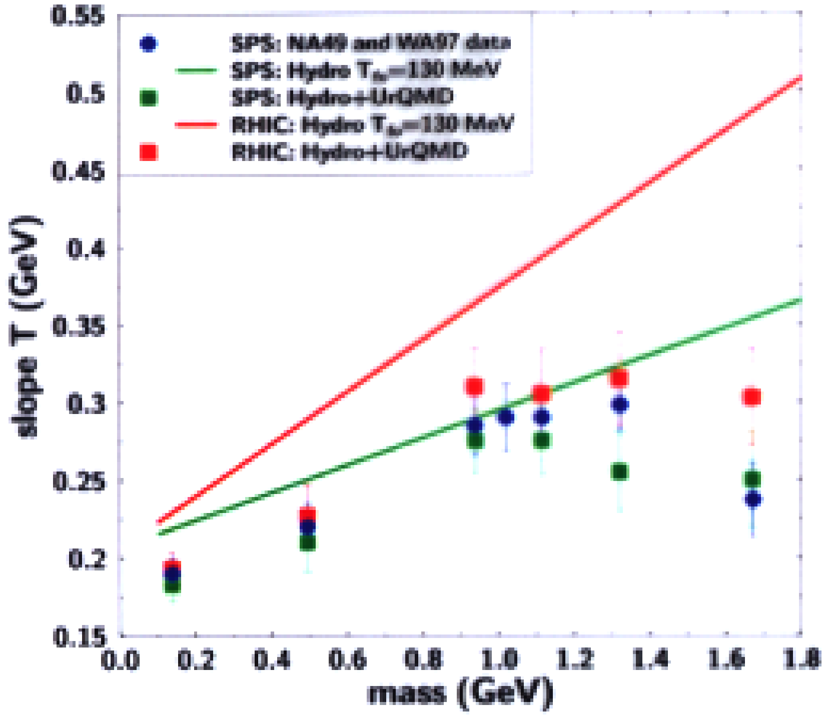
- B(Δy) provides clear signature of late stage hadronization

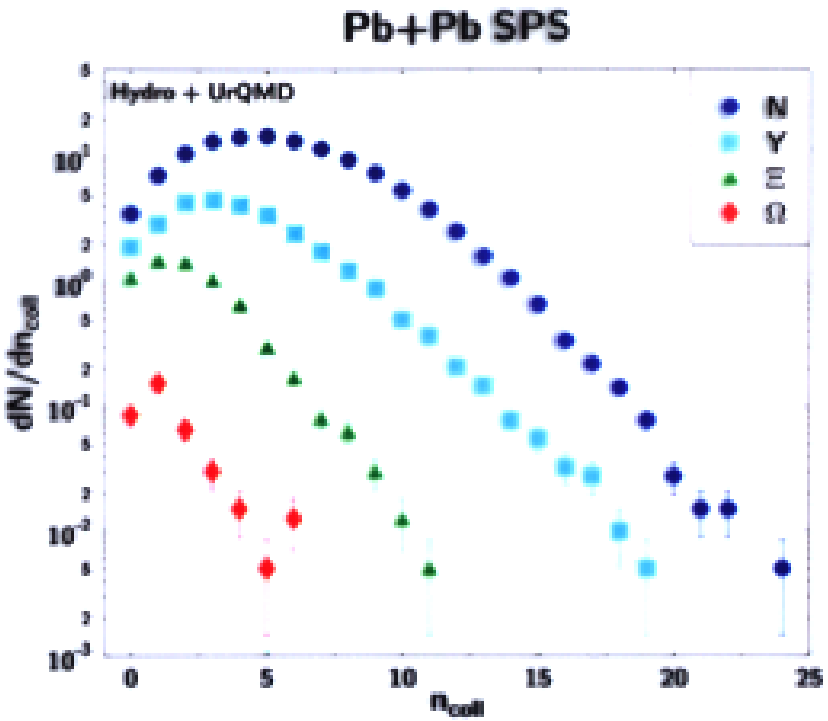
Chemical Freeze-Out at the Phase Boundary?

- ❖ Does the chemical composition of the system significantly change in the hadronic phase?
- ❖ Is the chemical composition indicative of conditions at hadronization?
- (anti-)baryon multiplicities change by up to 40%
- Kaon multiplicities are affected on the order of 10-20%
- ➢ hadronic rescattering significantly changes chemical composition
- ➢ no chemical freeze-out at phase boundary



Flavor Dynamics: Radial Flow

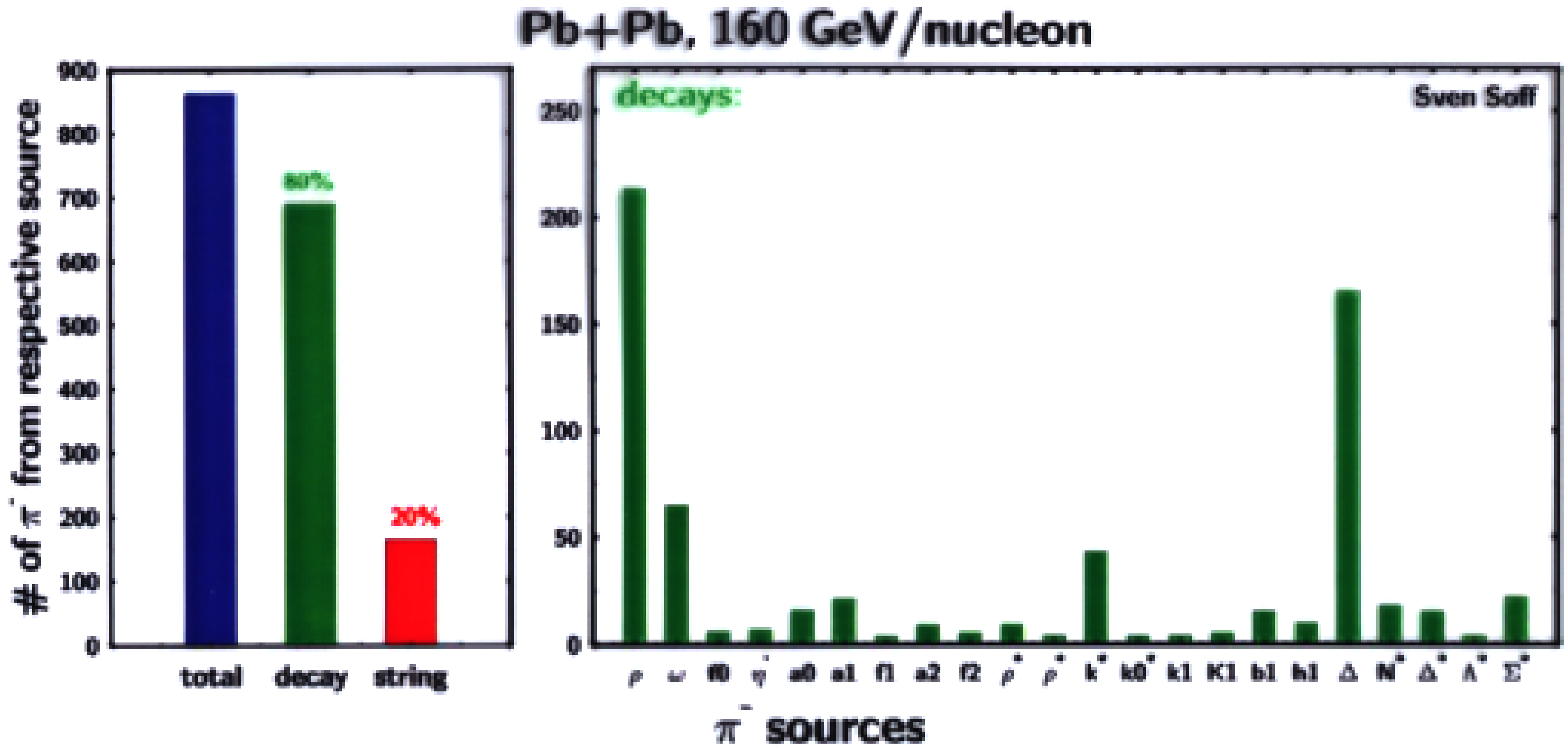




- Hydro: linear mass-dependence of slope parameter, strong radial flow
- Hydro+Micro: softening of slopes for multistrange baryons
  - ➢ early decoupling due to low collision rates
  - ➢ nearly direct emission from the phase boundary

Freeze-Out: Direct Emission vs. Rescattering

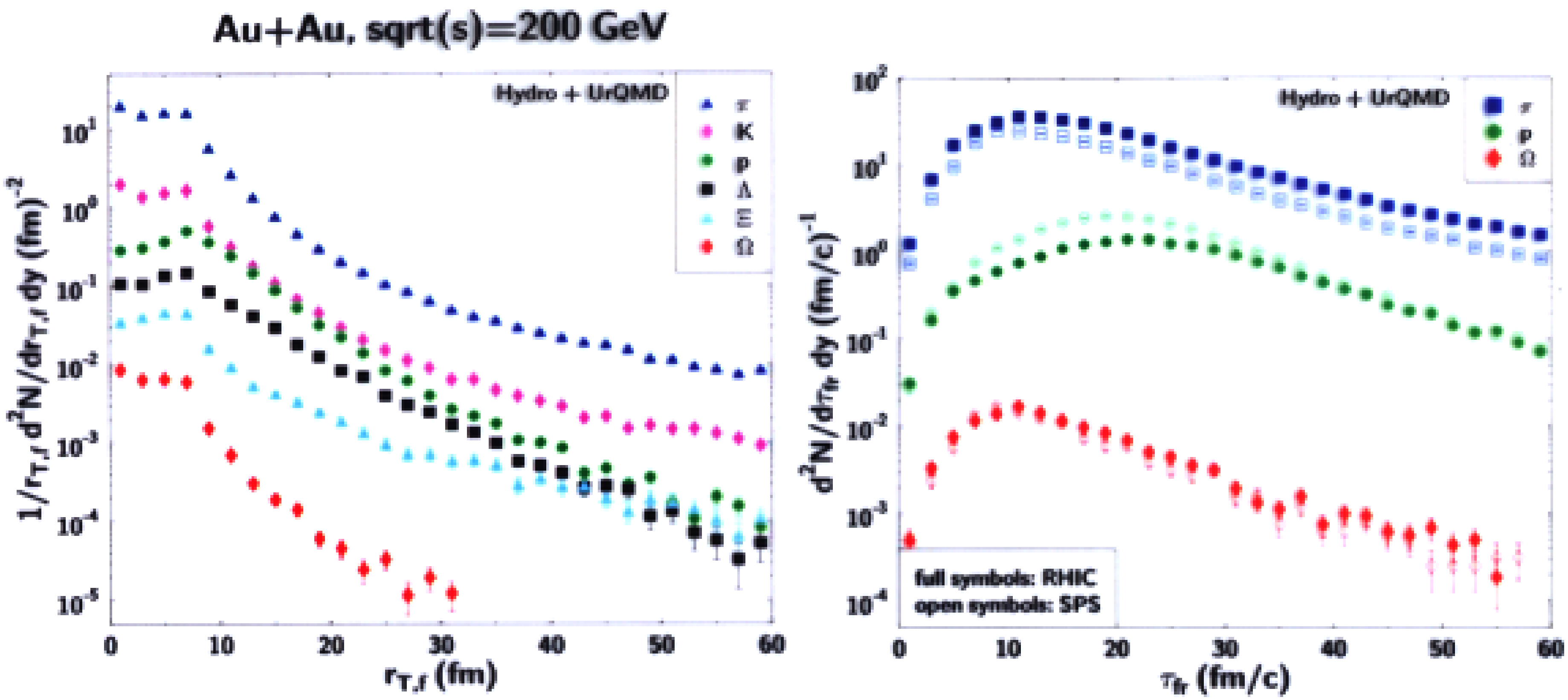
example: pion sources in a string/hadron model



- decays from ρ, Δ_{1232}, ω and K* give largest contribution

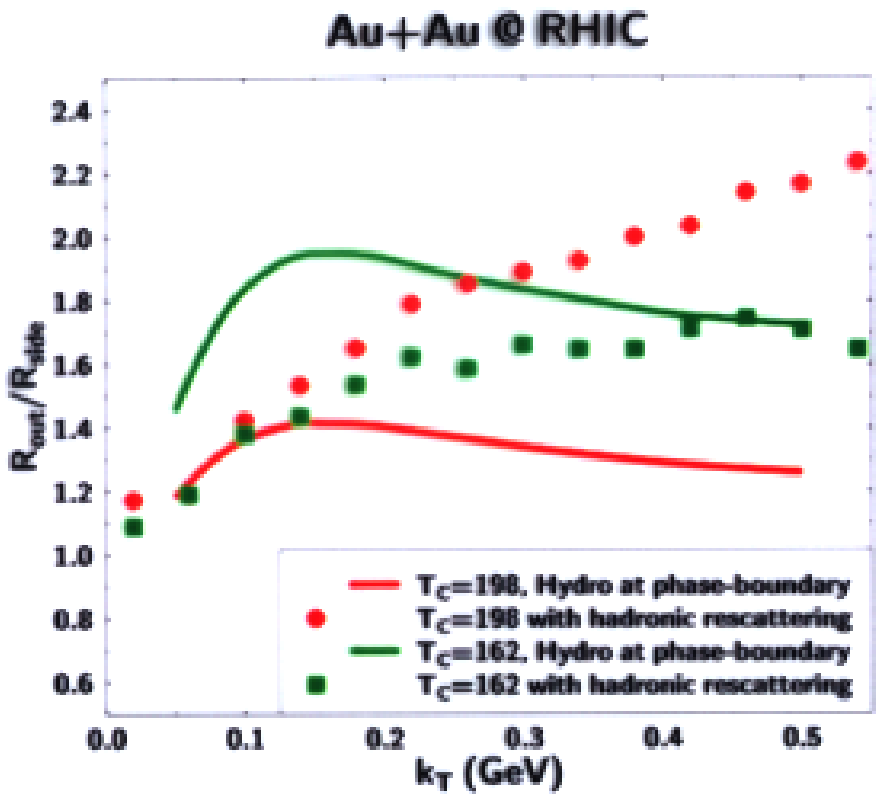
➢ secondary interactions and feeding dominate over direct production

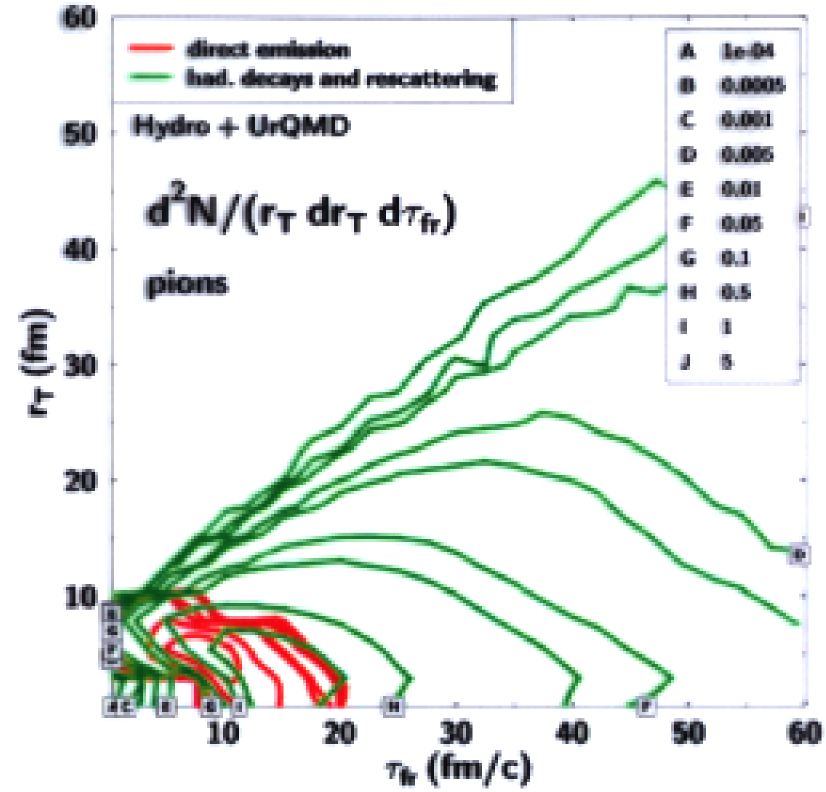
Freeze-Out: Flavor Dependence



- ➢ no sharp freeze-out: broad, flavor-dependent distributions
- ➢ only very small difference in lifetime from SPS to RHIC
  - use HBT as tool to investigate freeze-out behavior

HBT: QGP Lifetime vs. Hadronic Halo





- large R_{out}/R_{side} has been proposed as indicator of long-lived QGP
- inclusion of hadronic phase: only weak sensitivity to initial conditions
- ➢ long-lived dissipative hadronic phase dominates correlation signal
- ➢ dissipative hadronic phase: unavoidable consequence of thermalized QGP

Summary

- Transport Models
  - no single model ideally suited for entire reaction evolution
  - different concepts/degrees of freedom needed for different reaction stages
- Kinetic Evolution
  - continuous evolution of momentum scale, coupling constant
  - energy density larger than ε_{crit} even at the SPS
  - Balance Functions may probe hadronization time
- Hadrochemistry and Flavor Dynamics
  - hadronic phase changes hadrochemistry and spectral shapes
  - radial flow sensitive to flavor dynamics
- Freeze-out
  - continuous, flavor-dependent process
  - HBT insensitive to early reaction stages – probes hadronic halo